# On the photometric variability of blue supergiants in NGC 300 and its impact on the Flux-weighted Gravity–Luminosity Relationship[1]

Fabio Bresolin

*Institute for Astronomy, 2680 Woodlawn Drive, Honolulu, HI 96822; bresolin@ifa.hawaii.edu*

Grzegorz Pietrzyński

*Universidad de Concepción, Departamento de Fisica, Casilla 160-C, Concepción, Chile and Warsaw University Observatory, Al. Ujazdowskie 4, 00-478, Warsaw, Poland; pietrzyn@hubble.cfm.udec.cl*

Wolfgang Gieren

*Universidad de Concepción, Departamento de Fisica, Casilla 160-C, Concepción, Chile; wgieren@coma.cfm.udec.cl*

Rolf-Peter Kudritzki, Norbert Przybilla

*Institute for Astronomy, 2680 Woodlawn Drive, Honolulu HI 96822; kud@ifa.hawaii.edu, nob@ifa.hawaii.edu*

and

Pascal Fouqué

*Observatoire de Paris, LESIA, 5 Place Jules Janssen, F-92195 Meudon Cedex, France; pfouque@eso.org*

## ABSTRACT

We present a study of the photometric variability of spectroscopically confirmed supergiants in NGC 300, comprising 28 epochs extending over a period of five months. We find 15 clearly photometrically variable blue supergiants in a sample of nearly 70 such stars, showing maximum light amplitudes ranging from

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[1]Based on observations obtained with the 2.2m ESO/MPI telescope at the European Southern Observatory, as part of proposal 163.N-0210.

0.08 to 0.23 magnitudes in the $V$ band, and one variable red supergiant. We show their light curves, and determine semi-periods for two A2 Ia stars. Assuming that the observed changes correspond to similar variations in the bolometric luminosity, we test for the influence of this variability on the Flux-weighted Gravity–Luminosity Relationship and find a negligible effect, showing that the calibration of this relationship, which has the potential to measure extragalactic distances at the Cepheid accuracy level, is not affected by the stellar photometric variability in any significant way.

*Subject headings:* galaxies: individual (NGC 300) — galaxies: stellar content — stars: early-type — stars: supergiants — stars: variables: other

## 1. Introduction

The photometric and spectral variability has been established as a characterizing feature of supergiant stars already a few decades ago (Abt 1957, Rosendhal & Wegner 1970, Maeder & Rufener 1972, Rosendhal 1973, Sterken 1977), affecting virtually all luminous stars during their post-main sequence evolution. The light variations appear to be cyclic, characterized by semi-regular, rather than strictly periodic, patterns, obeying a semi-period–luminosity–color relationship (Burki 1978, Maeder 1980) analogous to the relation valid for Cepheids, with timescales ranging from a few days (early B supergiants) to hundreds of days (red supergiants). The maximum light amplitudes, on the order of 0.1 mag, increase with stellar luminosity, and reach in the hot star domain a local maximum for early-B supergiants (Appenzeller 1972, Maeder 1980, van Genderen 1989). The presence of photometric micro-variations on scales $\Delta m < 0.2$ mag typifies variable massive OBA supergiants, or $\alpha$ Cyg variables following the General Catalogue of Variable Stars (Kholopov et al. 1985; see also reviews by Sterken 1989 and van Genderen 1991, 2001).

The existence of a semi-period–luminosity–color relationship suggests pulsational instabilities as the driving mechanism for the observed variability, where stochastic processes determine the quasi-regularity. Several clues, including the large discrepancy between the theoretical periods for radial pulsations in the fundamental mode and the observed ones (Percy & Welch 1983, van Genderen 1985), together with color variations smaller than predicted (van Genderen 1986), indicate that non-radial oscillations are at work in blue supergiants (Maeder 1986, Baade 1992), possibly appearing in connection with evolutionary stages past the red supergiant phase (Lovey et al. 1984, Schaller 1990). Alternative or additional mechanisms have been proposed to explain the observed photometric and spectroscopic variability, such as orbital motions in binary systems (Harmanec 1987). In the

case of late-B and early-A supergiants the variability of spectral line profiles originating in the photosphere is consistent with non-radial pulsation modes, while rotational modulation appears to be affecting the extended stellar wind regions (Kaufer et al. 1996, 1997).

Regardless of the physical reasons for the observed variability, which concerns both the photospheric layers (as deduced from the photometric variations) and the extended winds of blue supergiants (from time series spectroscopic investigations, e.g. Kaufer et al. 1996, Rivinius et al. 1997, Stahl et al. 2003), it is interesting and necessary to determine its relevance when considering the use of blue supergiant stars as stellar candles (Bresolin 2003). Recently Kudritzki, Bresolin & Przybilla (2003) have discussed the preliminary calibration of the Flux-weighted Gravity–Luminosity Relationship (FGLR) and its potential use as an extragalactic distance indicator. As originally proposed, such a relation applies to late-B to early-A supergiants, which belong to the visually brightest stars in galaxies, thus allowing tests of its validity to be carried out in galaxies located well beyond the Local Group. Both the FGLR and the Wind Momentum–Luminosity Relationship (WLR, Kudritzki et al. 1999) rely on the measurement of the apparent visual magnitude of blue supergiants, which are then transformed to bolometric luminosities from knowledge of the spectral type. An assessment of the reliability of such methods should involve tests concerning their sensitivity to time-dependent stellar properties, such as the mass-loss rate (for the WLR), and to the above mentioned photometric micro-variations (FGLR and WLR).

'Normal' (non-LBV) blue supergiants have been rarely monitored for variability beyond the Magellanic Clouds. In this paper we report on a medium-term (five months) $V$ monitoring program of blue supergiants in the galaxy NGC 300. The main motivation for this work is to demonstrate that the FGLR is insensitive for all practical purposes to the micro-variations normally observed in B and A supergiants.

## 2. Observational data

The photometric measurements for the NGC 300 blue supergiants included in this study have been extracted from images obtained at the ESO/MPI 2.2 m telescope on La Silla, equipped with its Wide Field Imager 8 K $\times$ 8 K mosaic camera. These multi-epoch observations are part of the $BVRI$ Cepheid monitoring program described by Pietrzyński et al. (2002), where details on the calibration and the data reduction can be found. The data discussed in the current paper span the period 1999 July 31–2000 January 8, covered by observations on 28 different nights, mostly under photometric conditions, roughly grouped in five blocks of data separated by temporal gaps up to 43 days long. Only the $V$-band temporal sequence will be discussed here ($B$-band magnitudes have a somewhat less reliable

calibration, but still show variations similar to those observed in $V$).

Spectra of blue supergiants in NGC 300 have been obtained with the FORS1 multi-object spectrograph at the ESO Very Large Telescope by Bresolin et al. (2002a), and we restrict the following analysis to the spectroscopically confirmed B- and A-type supergiants. For the individual stars we adopt the nomenclature introduced in the spectral catalog presented in that paper.

## 3. Variability of blue supergiants: detection and light curves

The standard deviation from the mean magnitude and the maximum light amplitude were taken as a measure of the stellar variability. We selected stars having small dispersion in magnitude to serve as comparison stars in order to define the observational uncertainty, $\sigma_0$, as a function of magnitude. We then arbitrarily retained for further analysis only those objects for which $\sigma \geq 2\,\sigma_0$ (Fig. 1). A selection based on the maximum light amplitude generates a similar sample of stars. This procedure is justified since we are not aiming at a complete compilation of variable supergiants in NGC 300, but instead at an analysis of those spectroscopically confirmed supergiants displaying the largest variability, since these will have a maximum effect on the FGLR.

The 16 stars satisfying the selection criterion are labeled in Fig. 1 with the identification number introduced by Bresolin et al. (2002a). Their mean apparent $V$ and absolute $M_V$ magnitudes, $B-V$ colors, standard deviations in the $V$ magnitude $\sigma_{\rm V}$, maximum light amplitudes $A_{\rm v}$ and spectral types are summarized in Table 1. $M_V$'s have been determined assuming a distance modulus $m-M=26.53$ (Freedman et al. 2001), and estimating the reddening (and the extinction with $R_V=3.1$) based on the difference between the observed $B-V$ and the expected color index for the given spectral type. The photometric measurements differ slightly (mostly at the 0.01-0.02 mag level) from those in Table 2 of Bresolin et al. (2002a), as a result of improved zero-points and photometry. All stars in Table 1 are blue supergiants (early-B to mid-A), with the exception of A5, a red supergiant, which shows the largest light variation among the detected variables, apparently occuring over a period longer than our observing window. The WN11 (or Ofpe/WN9) star B16 analyzed by Bresolin et al. (2002b) also appears in Table 1.

The $V$ light curves of the selected variable stars are displayed in Fig. 2. Despite the gaps in the temporal sequence, photometric variations occuring on timescales of tens of days can be easily detected in most cases, often superimposed on variations at higher frequency.

## 4. Period search

The periodicity of the photometric sequences has been analyzed utilizing the Phase Dispersion Minimization algorithm introduced by Stellingwerf (1978), as implemented in the IRAF astronomical data reduction package. Our goal was simply to check whether semi-periods comparable in length to those of Galactic and Magellanic Cloud supergiants could be found also in NGC 300, aware of the fact that the irregular sampling of the data within our observing window is far from being optimal for an accurate frequency analysis.

Only for two stars a clear isolated minimum in the $\Theta$ statistics (which is defined to vary between 0 and 1, see Stellingwerf 1978) is unambiguously identified, leading to a reasonable determination of the semi-periods. Such is the case of D12 ($\Theta = 0.06$, P = 72 days) and A10 ($\Theta = 0.40$, P = 96 days), both of spectral type A2 Ia, shown in the phase diagrams of Fig. 3 (the uncertainty in the quoted periods is on the order of 10%). For the remaining stars in the sample $\Theta$ lies between 0.4 and 0.75, and a unique semi-period determination was not possible, with multiple phase dispersion minima occuring at periods roughly between a few days and 30-40 days. The phased light curves for these stars display a large amount of scatter, but this is typical of the light variations of blue supergiants, as multiple pulsation modes can be excited in blue supergiants (Lucy 1976, van Gent & Lamers 1986, van Genderen, Sterken & de Groot 1998). We note that the semi-periods found for the two A2 supergiants D12 and A10, of absolute magnitude $M_V = -8.3$ and $-7.8$, respectively, are roughly twice as long as those listed for similar stars in the Milky Way by Burki (1978). Fundamental periods calculated from the respective stellar parameters are 42 days (D12) and 27 days (A10) (Schaller 1990).

## 5. Impact on the Flux-weighted gravity–Luminosity Relationship

The findings of the previous sections confirm that the typical photometric micro-variability of blue supergiants, known from studies in the Milky Way and the Magellanic Clouds, is also found in our NGC 300 sample. The advantage of these data from the extragalactic point of view is that they allow us to carry out a simple but important test concerning the effect of the stellar variability on the FGLR. Given the typical amplitude of the broad-band photometric variations, $\sim 0.1$ mag, it is reasonable not to expect a significant effect, but a quantification of its size is desirable.

The FGLR, introduced by Kudritzki, Bresolin & Przybilla (2003), expresses the proportionality between the bolometric magnitude of a blue supergiant and its flux-weighted gravity during its evolution across the Hertzprung-Russell diagram at roughly constant luminosity:

$$M_{\rm bol} = 3.71\,\log(g/T_{\rm eff,4}^4)\, - 13.49 \qquad (1)$$

where $T_{\rm eff,4} = T_{\rm eff}/10^4\,K$, with slope and zero-point fixed by a preliminary calibration, based on the stellar parameters determined for stars in different galaxies: Milky Way, Magellanic Clouds, NGC 6822, M31, M33, NGC 300 and NGC 3621.

It is not clear whether during the semi-periodic light variations the bolometric magnitude remains rigorously constant. If that were the case, then the FGLR would be unaffected by the blue supergiant variability. On the other hand, one could imagine that the detected light variations are symptomatic of small changes in the total luminosity (as in the pulsating massive star models by Dorfi & Gautschy 2000). In this case, and lacking additional constraints, we can test the corresponding effect on the FGLR by determining the relationship at different epochs, letting $M_{\rm bol}$ vary by an amount equal to the broad-band variability. The flux-weighted gravity $g/T_{\rm eff,4}^4$ is kept constant, since spectra for the derivation of gravity and $T_{\rm eff}$ are available for one single epoch only, and therefore we have no way of estimating their possible variations. Only spectral time series would allow us to verify if and how the stellar parameters change during the cyclic changes.

Under these assumptions, we have calculated slope and zero-point of the FGLR at each available epoch, using our photometric temporal sequence for the NGC 300 blue supergiants considered by Kudritzki et al. (2003), i.e. 14 stars of spectral type between B8 and A2. The stellar parameters for these stars, as calculated by Kudritzki et al. (2003), are summarized in Table 2, and the whole set of $V$ magnitudes at 28 different epochs is given in Table 3 (the uncertainty of the individual measurements is on the order of 0.01–0.02 mag). *The zero-point and rms of the linear fit are found to be affected below the 10% level, when compared with the regression shown for NGC 300 stars alone (rms $\simeq$ 0.2 mag) by Kudritzki et al. (2003), with variations in the slope only up to 4%.* It is clear that the supergiant variability introduces a negligible effect on the resulting FGLR, which will remain negligible even when an improved calibration of the relation, including its possible dependence on the stellar metallicity, will become available in the near future.

In conclusion, the FGLR appears to provide an extragalactic distance indicator which is robust against supergiant photometric variability, provided that the number of stars considered per galaxy is sufficiently large ($n \sim 10$). As for the future work, besides improving the calibration in terms of statistics and metallicities, additional efforts are required to establish whether spectral variations are important for the derivation of the stellar parameters.

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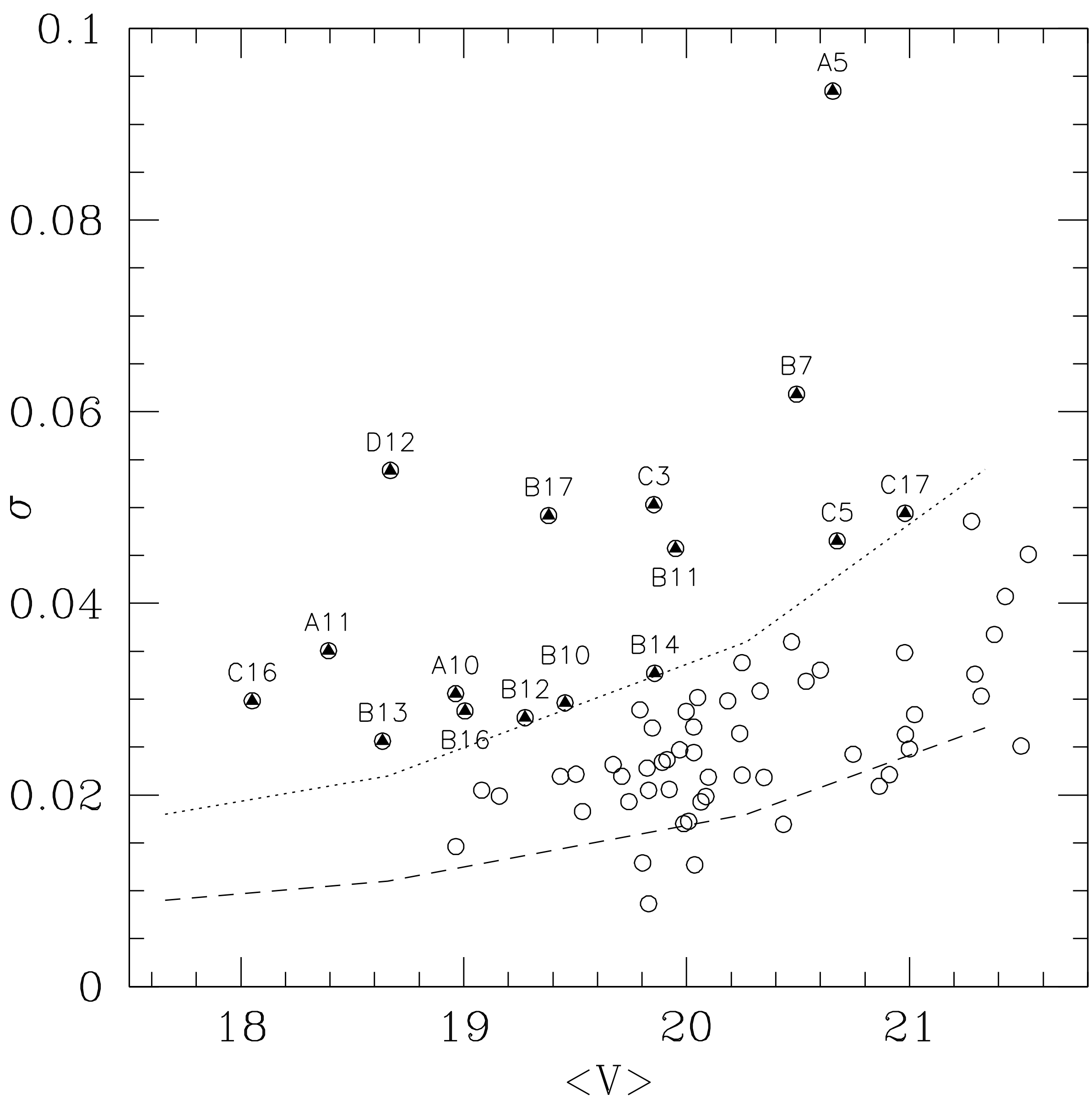


Fig. 1.— Standard deviation from the mean magnitude as a function of mean $V$ magnitude for the blue supergiant sample studied spectroscopically in NGC 300. The dashed line indicates the standard deviation measured for comparison stars, $\sigma_0$, while the dotted line is plotted at $\sigma = 2\,\sigma_0$. Stars above this limit are shown with filled symbols, and are labeled according to the spectral catalog of Bresolin et al. (2002a).

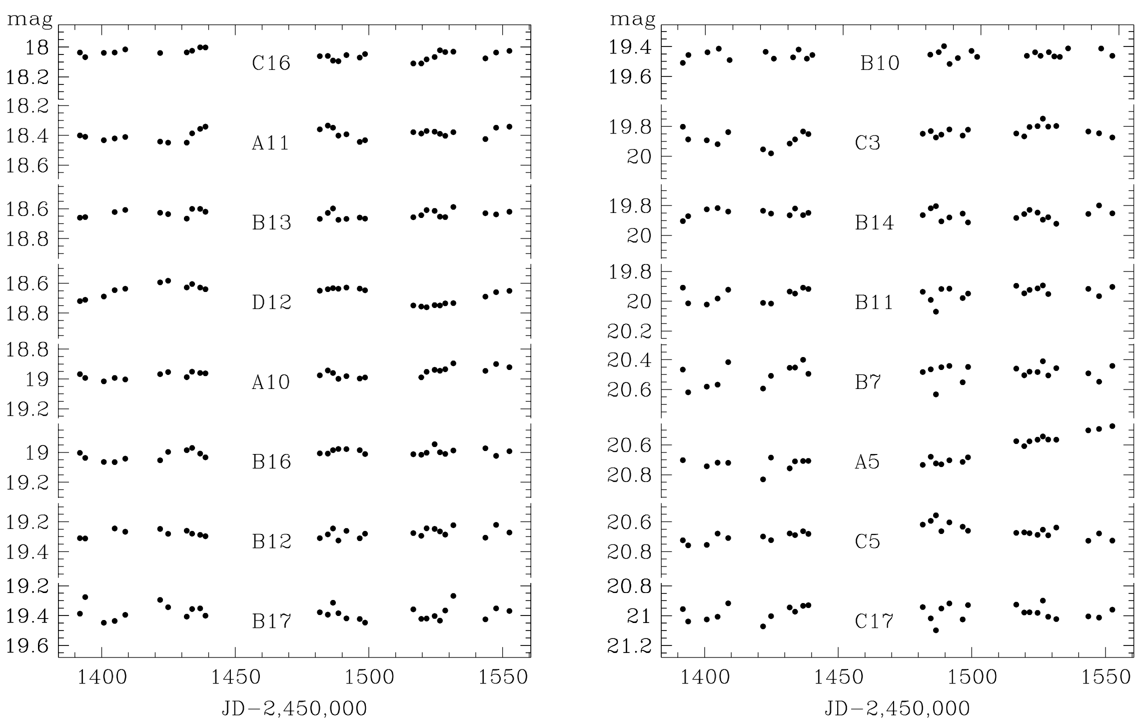


Fig. 2.— $V$-band light curves of the selected variable blue supergiants in NGC 300, in order of increasing magnitude.

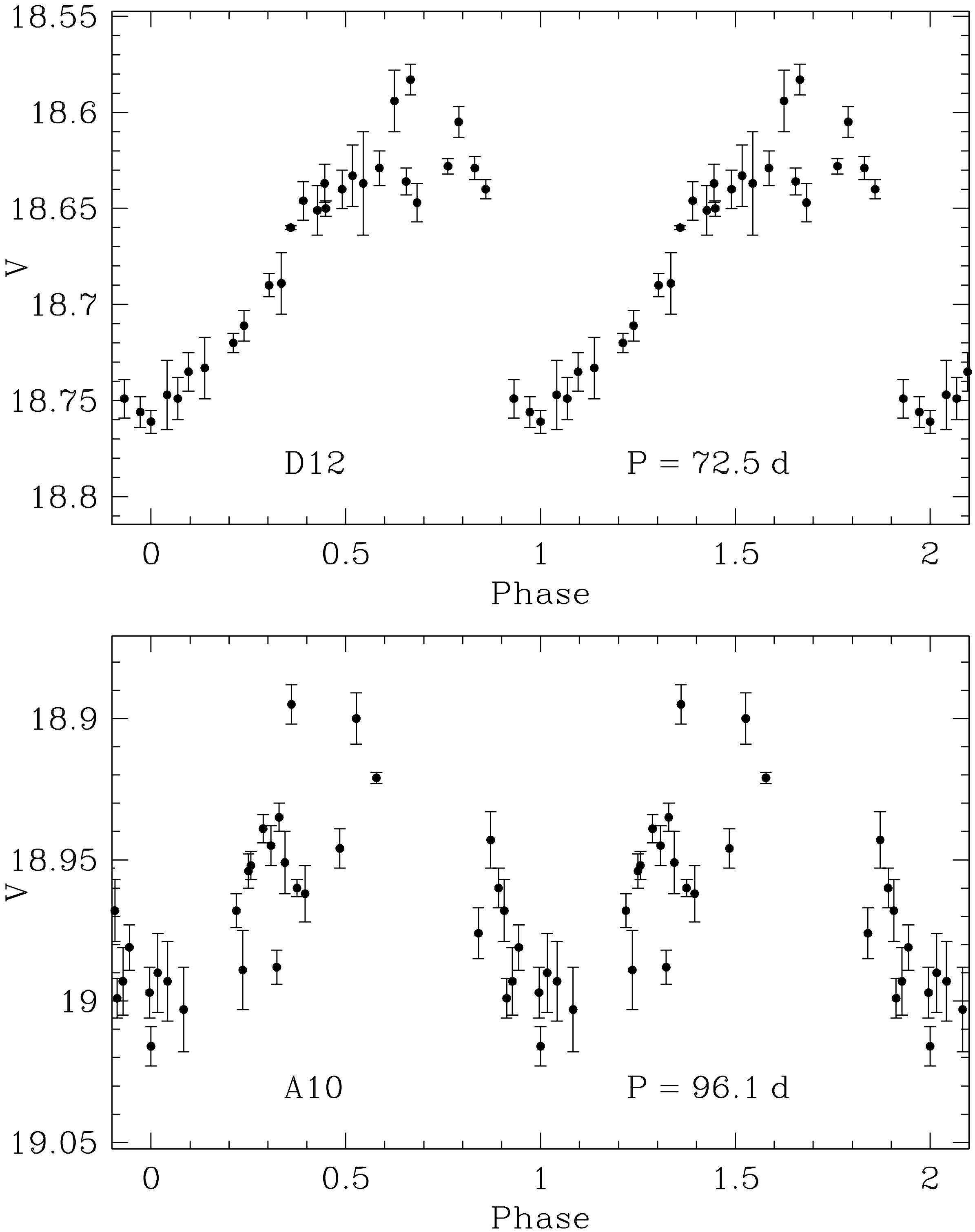


Fig. 3.— $V$-band phase diagrams for the A2 Ia stars D12 and A10, showing periodic or near-periodic photometric variations. For clarity the phase has been extended over two periods.

Table 1. Selected variables

| Supergiant ID | $<V>$ | $<M_V>$ | $<B-V>$ | $\sigma_V$ | $A_V$ | Spectral type |
|---|---|---|---|---|---|---|
| A5 ....... | 20.66 | $-6.02$[a] | 2.04 | 0.093 | 0.357 | Late |
| A10 ...... | 18.96 | $-7.72$ | 0.07 | 0.031 | 0.121 | A2 |
| A11 ...... | 18.39 | $-8.51$ | 0.10 | 0.035 | 0.114 | B8 |
| B7 ....... | 20.49 | $-6.29$ | $-0.08$ | 0.062 | 0.232 | B2 |
| B10 ...... | 19.45 | $-7.20$ | 0.06 | 0.030 | 0.119 | A2–A3 |
| B11 ...... | 19.95 | $-6.58$ | 0.04 | 0.046 | 0.176 | A5 |
| B12 ...... | 19.28 | $-7.56$ | $-0.11$ | 0.028 | 0.105 | B0.5 |
| B13 ...... | 18.63 | $-7.90$ | $-0.08$ | 0.026 | 0.086 | B3 |
| B14 ...... | 19.86 | $-6.73$ | 0.04 | 0.033 | 0.123 | A0 |
| B16 ...... | 19.01 | $-7.72$ | $-0.07$ | 0.029 | 0.120 | WN11 |
| B17 ...... | 19.38 | $-7.58$ | $-0.07$ | 0.049 | 0.180 | B0.5 |
| C3 ....... | 19.85 | $-6.93$ | 0.06 | 0.050 | 0.233 | B8–B9 |
| C5 ....... | 20.67 | $-6.20$ | $-0.05$ | 0.046 | 0.201 | B2 |
| C16 ...... | 18.05 | $-8.70$ | 0.07 | 0.030 | 0.108 | B9 |
| C17 ...... | 20.98 | $-5.70$[a] | 0.14 | 0.049 | 0.199 | Composite |
| D12 ...... | 18.67 | $-8.32$ | 0.18 | 0.054 | 0.178 | A2 |

[a]assuming $E(B-V) = 0.05$

Table 2. FGLR supergiants in NGC 300 – Stellar parameters

| Supergiant ID | Spectral type | $T_{\rm eff}$ $(K)$ | $\log g$ | $E(B-V)$ | Bolometric correction |
|---|---|---|---|---|---|
| A8 ....... | B9-A0 | 10,000 | 1.60 | 0.02 | $-0.42$ |
| A10 ...... | A2 | 9,000 | 1.30 | 0.05 | $-0.22$ |
| A11 ...... | B8 | 12,000 | 1.42 | 0.12 | $-0.91$ |
| A13 ...... | B8 | 12,000 | 1.95 | 0.02 | $-0.81$ |
| A18 ...... | B8 | 12,000 | 1.90 | 0.05 | $-0.83$ |
| B10 ...... | A2-A3 | 8,800 | 1.37 | 0.04 | $-0.14$ |
| C6 ....... | A0 | 9,500 | 1.60 | 0.07 | $-0.28$ |
| C7 ....... | A0 | 9,500 | 1.68 | 0.03 | $-0.31$ |
| C8 ....... | B8 | 12,000 | 1.90 | 0.03 | $-0.83$ |
| C12 ...... | B9-A0 | 9,800 | 1.80 | 0.06 | $-0.40$ |
| C16 ...... | B9 | 10,500 | 1.30 | 0.07 | $-0.56$ |
| D12 ...... | A2 | 9,000 | 1.05 | 0.15 | $-0.27$ |
| D13 ...... | A0 | 9,500 | 1.35 | 0.03 | $-0.31$ |
| D17 ...... | B9-A0 | 10,000 | 1.60 | 0.05 | $-0.39$ |

Table 3. FGLR supergiants in NGC 300 – $V$-magnitude temporal sequence

| Supergiant | Julian Date − 2,450,000 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | 1391.86 | 1393.86 | 1400.81 | 1404.88 | 1408.85 | 1421.87 | 1424.85 | 1431.83 | 1433.83 | 1436.84 | 1438.84 | 1481.61 | 1484.64 | 1486.59 |
| | 1488.57 | 1491.59 | 1496.57 | 1498.59 | 1516.62 | 1519.59 | 1521.60 | 1524.60 | 1526.57 | 1528.58 | 1531.60 | 1543.57 | 1547.61 | 1552.58 |
| A8 ....... | 19.45 | 19.48 | 19.46 | 19.44 | 19.44 | 19.47 | 19.43 | 19.45 | 19.43 | 19.41 | 19.42 | 19.46 | 19.40 | 19.41 |
| | 19.45 | 19.43 | 19.45 | 19.43 | 19.43 | 19.44 | 19.43 | 19.44 | 19.44 | 19.43 | 19.39 | 19.44 | 19.39 | 19.41 |
| A10 ...... | 18.97 | 18.99 | 19.02 | 18.99 | 19.00 | 18.97 | 18.95 | 18.99 | 18.95 | 18.96 | 18.96 | 18.98 | 18.94 | 18.96 |
| | 19.00 | 18.98 | 18.99 | 18.99 | ··· | 18.99 | 18.95 | 18.94 | 18.94 | 18.93 | 18.89 | 18.95 | 18.90 | 18.92 |
| A11 ...... | 18.40 | 18.41 | 18.43 | 18.42 | 18.41 | 18.44 | 18.45 | 18.45 | 18.39 | 18.36 | 18.34 | 18.36 | 18.33 | 18.35 |
| | 18.40 | 18.39 | 18.44 | 18.43 | 18.38 | 18.39 | 18.37 | 18.38 | 18.39 | 18.40 | 18.38 | 18.42 | 18.35 | 18.34 |
| A13 ...... | 19.84 | 19.83 | 19.83 | 19.83 | 19.83 | 19.82 | 19.80 | 19.83 | 19.81 | 19.79 | 19.82 | 19.84 | 19.81 | ··· |
| | 19.85 | 19.86 | 19.86 | ··· | 19.83 | 19.82 | 19.81 | 19.82 | 19.83 | 19.83 | 19.76 | 19.84 | 19.77 | 19.82 |
| A18 ...... | 20.01 | 20.00 | 20.01 | 19.99 | 19.98 | 19.96 | 19.98 | 20.06 | 20.01 | 20.01 | 20.01 | 20.00 | 19.95 | ··· |
| | 20.05 | 20.03 | 20.01 | 20.02 | 20.00 | 19.99 | 19.98 | 19.99 | 20.02 | 19.98 | 19.96 | 19.98 | 19.93 | 20.01 |
| B10 ...... | 19.51 | 19.46 | 19.44 | 19.41 | 19.49 | 19.44 | 19.48 | 19.47 | 19.42 | 19.48 | 19.46 | 19.45 | 19.44 | 19.40 |
| | 19.52 | 19.48 | 19.43 | 19.47 | 19.46 | 19.44 | 19.46 | 19.44 | 19.47 | 19.47 | 19.41 | 19.41 | 19.46 | ··· |
| C6 ....... | 19.90 | 19.95 | 19.94 | 19.94 | 19.88 | 19.90 | 19.92 | 19.91 | 19.90 | 19.88 | 19.89 | 19.92 | 19.92 | 19.94 |
| | 19.93 | 19.88 | 19.95 | 19.91 | 19.89 | 19.91 | 19.90 | 19.93 | 19.87 | 19.91 | 19.88 | 19.92 | 19.93 | 19.92 |
| C7 ....... | 20.34 | 20.38 | 20.37 | 20.34 | 20.35 | 20.37 | 20.34 | 20.35 | 20.33 | 20.32 | 20.32 | 20.36 | 20.35 | 20.38 |
| | 20.38 | 20.33 | 20.39 | 20.35 | 20.33 | 20.35 | 20.33 | 20.35 | 20.32 | 20.36 | 20.31 | 20.34 | 20.34 | 20.33 |
| C8 ....... | 20.01 | 20.09 | 20.07 | 20.08 | 20.03 | 20.09 | 20.05 | 20.04 | 20.05 | 20.01 | 20.01 | 20.03 | 20.02 | 20.11 |
| | 20.06 | 20.01 | 20.10 | 20.04 | 20.03 | ··· | 20.03 | 20.06 | 20.02 | 20.09 | 20.07 | 20.04 | 20.05 | 20.03 |
| C12 ...... | 20.16 | 20.19 | 20.16 | 20.14 | 20.16 | 20.16 | 20.17 | 20.16 | 20.15 | 20.14 | 20.16 | 20.19 | 20.18 | 20.20 |
| | 20.23 | 20.18 | 20.22 | 20.21 | 20.20 | 20.21 | 20.17 | 20.21 | 20.16 | 20.22 | 20.16 | 20.23 | 20.22 | 20.23 |
| C16 ...... | 18.04 | 18.07 | 18.04 | 18.04 | 18.02 | 18.04 | ··· | 18.04 | 18.02 | 18.00 | 18.00 | 18.06 | 18.06 | 18.09 |
| | 18.09 | 18.05 | 18.07 | 18.05 | 18.11 | 18.11 | 18.08 | 18.07 | 18.02 | 18.03 | 18.03 | 18.08 | 18.04 | 18.03 |
| D12 ...... | 18.72 | 18.71 | 18.69 | 18.65 | 18.64 | 18.59 | 18.58 | 18.63 | 18.60 | 18.63 | 18.64 | 18.65 | 18.64 | 18.63 |
| | 18.64 | 18.63 | 18.64 | 18.65 | 18.75 | 18.76 | 18.76 | 18.75 | 18.75 | 18.73 | 18.73 | 18.69 | 18.66 | 18.65 |
| D13 ...... | 18.98 | 18.97 | 18.99 | 18.94 | 18.96 | 18.98 | 18.96 | 18.99 | 18.97 | 18.97 | 18.96 | 18.97 | 18.96 | 18.96 |
| | 18.96 | 18.98 | 18.97 | 18.98 | 18.95 | 18.94 | 18.95 | 18.96 | 18.98 | 18.97 | 18.94 | 18.95 | 18.95 | 18.96 |
| D17 ...... | 19.50 | 19.51 | 19.52 | 19.53 | 19.58 | 19.53 | 19.52 | 19.55 | 19.53 | 19.53 | 19.53 | 19.54 | 19.54 | 19.53 |
| | 19.57 | 19.57 | 19.54 | 19.55 | 19.51 | 19.52 | 19.53 | 19.53 | 19.52 | 19.51 | 19.51 | 19.53 | 19.53 | 19.55 |